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A methodology to guide the selection of composite materials in a wind turbine rotor blade design process

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Abstract. This work is concerned with the development of an optimization methodology for the composite materials used in wind turbine blades. Goal of the approach is to guide designers in the selection of the different materials of the blade, while providing indications to composite manufacturers on optimal trade-offs between mechanical properties and material costs. The method works by using a parametric material model, and including its free parameters amongst the design variables of a multi-disciplinary wind turbine optimization procedure. The proposed method is tested on the structural redesign of a conceptual 10 MW wind turbine blade, its spar caps and shell skin laminates being subjected to optimization. The procedure identifies a blade optimum for a new spar cap laminate characterized by a higher longitudinal Young's modulus and higher cost than the initial one, which however in turn induce both cost and mass savings in the blade. In terms of shell skin, the adoption of a laminate with intermediate properties between a bi-axial one and a tri-axial one also leads to slight structural improvements.

1. Introduction

The current trend of developing multi-MW offshore wind turbine rotors challenges wind turbine blade manufacturers from many technical points of view. In the fields of aerodynamics, structural design, control and systems engineering new design solutions arise to push the development of very large machines, while simultaneously minimizing the cost of energy from wind. In this context, complex multi-disciplinary design tools have been developed to assist designers and help them identify the best trade-offs among the different disciplines. Significant efforts have been put in the enlargement of the solution space by including an ever increasing set of parameters as optimization variables (among several others, see for example [1-3]).

This trend is however far from being complete, and the list of a-priori decisions is still long. For instance, the selection of the composite materials adopted in the different structural components of the blade is typically made upfront. This choice may be later changed, and the design repeated. However, a *constructive* way of finding the optimal material for a given component is still lacking. On the one side, the present approach is often very reasonable, as blade designers can generally only choose among a



discrete list of materials. On the other, the assumption may be suboptimal and composite manufacturers may offer rich catalogues with more suitable products. Moreover, composites could also be tailored based on designers' requests. This, clearly within a range of possible solutions, offers the opportunity of looking at tradeoffs between mechanical properties and laminate costs.

In this study, a rotor blade structural design tool is coupled with a parametric model of composite materials, with a two-fold goal. The first objective is to relieve the blade designer from the a-priori selection of the composites and leave this decision to a numerical optimization solver. The second goal is to extract indications that can be used by composite manufacturers during the design and development of dedicated products for the wind energy industry.

2. Methodology

2.1. Design framework

Cp-Max is the design tool used in this study [3,4]. The code is based on the high-fidelity aeroservoelastic multibody-based software Cp-Lambda [5] coupled with the 2D finite element cross sectional analysis code ANBA (ANisotropic Beam Analysis) [6]. Cp-Max uses several nested optimization loops in one single algorithm to perform the integrated design of rotor shape, blade structure, tower structure and wind turbine control laws. The procedures result in a number of constrained optimization problems solved by a sequential quadratic programming (SQP) solver, which computes the gradients by means of finite differences. In this framework, the merit figure to be minimized by the overall design process is the cost of energy, which is calculated from detailed cost models [3].

Within Cp-Max, several optimization sub-loops identify optimal solutions that concur to the final wind turbine design. The focus of this study is on the blade structural optimization sub-loop, whose goal consists of minimizing the blade cost, which is estimated through the Sandia blade cost model [7], while satisfying a list of constraints. This typically includes frequency constraints together with a constraint on maximum allowable tip deflection as well as constraints on multi-directional stresses, strains, and fatigue damage, which are calculated with ANBA along a selection of blade sections. The constraints are computed using dynamic loads produced by running a user defined list of Design Load Cases (DLCs). In addition, the core of sandwich structures is also sized at the same locations along the blade to prevent buckling of the shell and webs panels [4].

The optimization variables of the structural code are represented by the thickness values of the various structural components at different stations along the span of the blade. In the present study, these quantities have been augmented with new optimization variables that index a parametric model of the composite materials. These new variables operate as indices within a list of composite laminates, in effect realizing the scanning of a continuous catalogue in search of the best possible material for the application at hand.

2.2. Catalogue of composite laminates

The parametric material model resembles a potential catalogue offered by composite manufacturers for different classes of laminates. In the catalogue, mechanical properties and costs characterize each laminate. The list of laminates chosen for this study consists of a combination of commercial glass-fiber-reinforced-plastic (GFRP) laminates from the Owens Corning database, together with publicly available data of GFRP laminates and of carbon-fiber-reinforced-plastic (CFRP) laminates from Ref. [8-10]. The unit cost of all fabrics and of the epoxy resin are assumed based on inputs from Owens Corning. Two classes of composite laminates are assumed to perform the studies presented in Sect. 3:

- Class-A: a unidirectional (UD) E-glass laminate (E-GFRP), a high modulus UD glass (H-GFRP), and a full carbon UD (F-CFRP) laminate. The three laminates show increasing longitudinal Young's modulus E_{11} and unit cost.
- Class-B: bi-axial GFRP (Bx-GFRP) and tri-axial GFRP (Tx-GFRP).

It is worth noting that the catalogue could be further expanded based on a larger availability of manufacturer's data in terms of mechanical properties and related costs of the products.

Table 1: Macro parameters of the INNWIND 10 MW wind turbine model.

Data	Value	Data	Value
Wind class	IEC 1A	Rated mech. power	10.0 MW
Hub height	119.0 m	Rotor diameter	178.3m
Cut-in	4 m/s	Cut-out	25 m/s
Rotor cone	4.65 deg	Nacelle up tilt	5.0 deg
Rotor solidity	4.66%	Max Vtip	90.0m/s
Blade mass	42 496 kg	Tower mass	628.0 t

Table 2: List of DLCs considered in the design study [11].

DLC	Condition	Wind	Faults
1.1	Power production	NTM	-
1.3	Power production	ETM	-
2.1	Power production plus fault	NTM	Grid loss
2.3	Power production plus fault	EOG	Grid loss
6.1	Parked, idling	EWM (50 years)	-
6.2	Parked, idling	EWM (50 years)	Grid loss
6.3	Parked, idling	EWM (50 years)	-

2.3. Interpolation scheme of mechanical properties and costs

Within the catalogue, different indexing schemes can be implemented based on the nature of the optimization solver. The current choice for Class-A is to use the non-dimensional E_{11} value as free index. A generic family member is obtained by interpolation among all other laminate properties and costs using a shape-preserving Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) scheme. Given the presence of only two laminates, a trivial linear interpolation is instead adopted for Class-B.

This continuous parametric approach has the clear weakness of potentially converging to unrealistic materials. This problem can however be limited by the inclusion of constraints and bounds, and it would also be alleviated by a richer and more detailed catalogue. In addition, the approach may also in principle lead to multiple local minima for the structural design solution. However, no sign of local minima has emerged in the tests conducted so far, and global optimization solvers could be adopted in the future in case of need, at possibly increased computational costs.

3. Applications

3.1. Wind turbine model and definition of the optimization variables

The proposed methodology is exercised on the INNWIND 10 MW [9], a conceptual wind turbine model obtained from the structural redesign of the DTU 10 MW reference wind turbine (RWT) [10]. The machine, whose macro configuration is described in Table 1, is equipped with an 86.35 m long blade presenting nine structural components: two spar caps, shell skin, three webs, leading edge (LE) and trailing edge (TE) reinforcements, and finally root reinforcement. E-GFRP is adopted in the spar caps, while Tx-GFRP in the shell skin. The DLCs included during the development of the wind turbine model are listed in Table 2 [11].

The blade is parameterized with a total of 71 optimization variables describing the thickness distributions along the span of the nine components. The position of each optimization variable is graphically represented in Table 3. In addition to these values, two further optimization variables are included in this study to represent the composite indices, which identify the mechanical properties and the cost of the laminate of the spar caps and the laminate of the shell skin.

3.2. Optimization of spar caps laminate – parametric analysis

As depicted in Fig. 1, a cost analysis of the baseline blade design returns the largest material cost associated to the spar caps, whose laminate selection is taken as the first target to be optimized. A parametric design process is then initiated modeling parametrically the three laminates from Class-A in

Table 3: Optimization variables of the blade structural design optimization. Each variable controls the thickness of a component at a specific blade span position.

#	Optimization variables	Span location [%]													
		0	1	2.5	5	10	22	26.8	30	45	65	80	90	95	99.8
14	Shell skin														
14	Spar caps														
11	First and second webs														
8	Third web														
9	TE reinforcement														
9	LE reinforcement														
6	Root reinforcement														

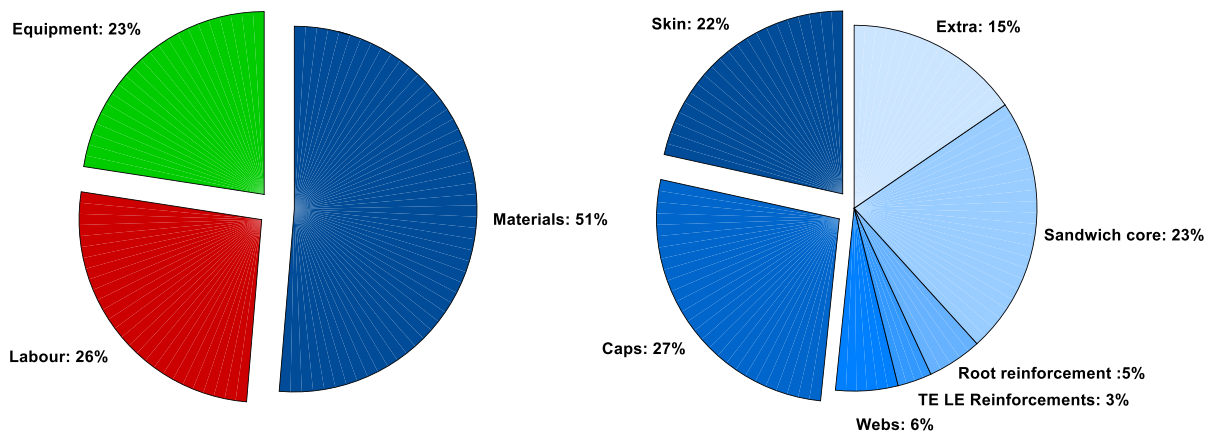


Figure 1: Blade cost breakdown (left) and blade material cost breakdown (right) of the reference blade calculated from the Sandia blade cost model.

the spar caps. For each laminate, a structural optimization with the 71 optimization variables listed in Table 3 is performed.

Overall, the initial selection for the spar cap laminate is found to be suboptimal and the simulations return beneficial effects from the adoption of H-GFRP. Indeed, as the baseline design is strongly tip deflection driven, and all other constraints are typically well satisfied at convergence, a more performant laminate in terms of E_{11} allows for a reduction of the overall blade cost thanks to thinner structural components and a more efficient structure. This trend is however valid up to a certain point, after which further improvements in laminate properties do not justify the higher fiber costs. In this framework, the adoption of F-CFRP in the spar caps indeed does not return a cost competitive rotor design, as the constraints on maximum allowable compressive stresses and strains limit the reductions of spar caps thicknesses, therefore confining the advantages of reduced composite volumes.

3.3. Optimization of spar caps laminate – automatic analysis

Within this study, a more ambitious goal is to identify the optimum solution in an automatic manner. To achieve this, the index controlling the laminate of the spar caps is made an active optimization variable, increasing the number of degrees of freedom of the problem to 72. Cp-Max is then run and the optimizer converges to a composite index 18.1% higher than the initial value, corresponding to an 18.1% and 15.0% growth in E_{11} and cost, respectively. While being close to H-GFRP, the final laminate has the E_{11} parameter that is 1.7% higher than H-GFRP, causing some extra small advantages, namely 0.7% and 0.1% in blade mass and cost respectively.

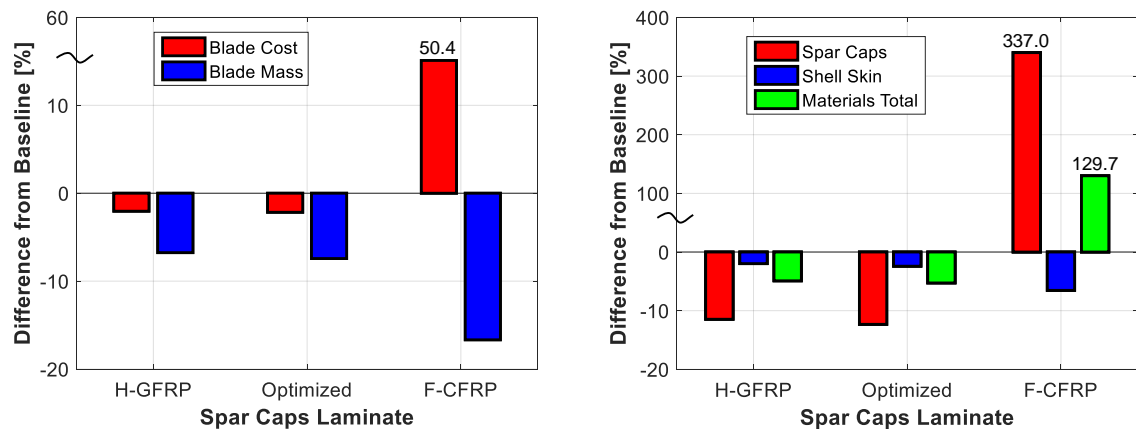


Figure 2: Blade cost and mass (left) and laminate costs (right) for the parametric and the automatic optimization study of the spar caps laminate.

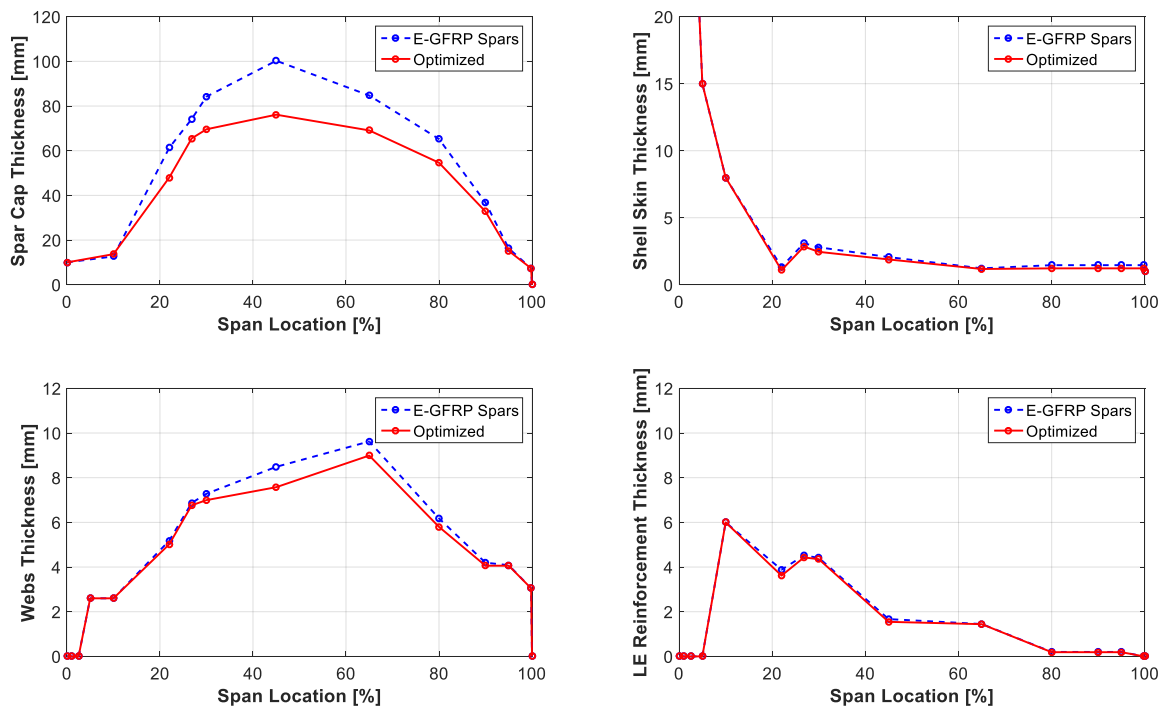


Figure 3: Comparison of thickness distributions along blade span for the reference and the blade design with optimized spar caps laminate.

The unit cost and all other mechanical properties of the final laminate are obtained from the PCHIP interpolation scheme, as described in Sect. 2.3. The diagrams in Fig. 2 show the results in terms of blade cost, blade mass and composite costs. Overall, the optimum blade design results in mass and cost savings equal to 7.4% and 2.2% compared to the baseline design. The comparison between the thickness of spar caps, shell skin, webs and LE reinforcement from the two blade designs is shown in Fig. 3, while bar plots showing the trends in strain and fatigue constraints are given in Fig. 4.

It is worth noting that no significant increase in computational costs can be attributed to the new degree of freedom, as this behaves similarly to any one of the other optimization variables controlling a component thickness along blade span. This causes the SQP solver to compute only one extra finite difference in order to estimate the gradient for cost function and nonlinear constraints. At the same time, it is observed that the overall number of iterations is not largely affected compared to previous blade

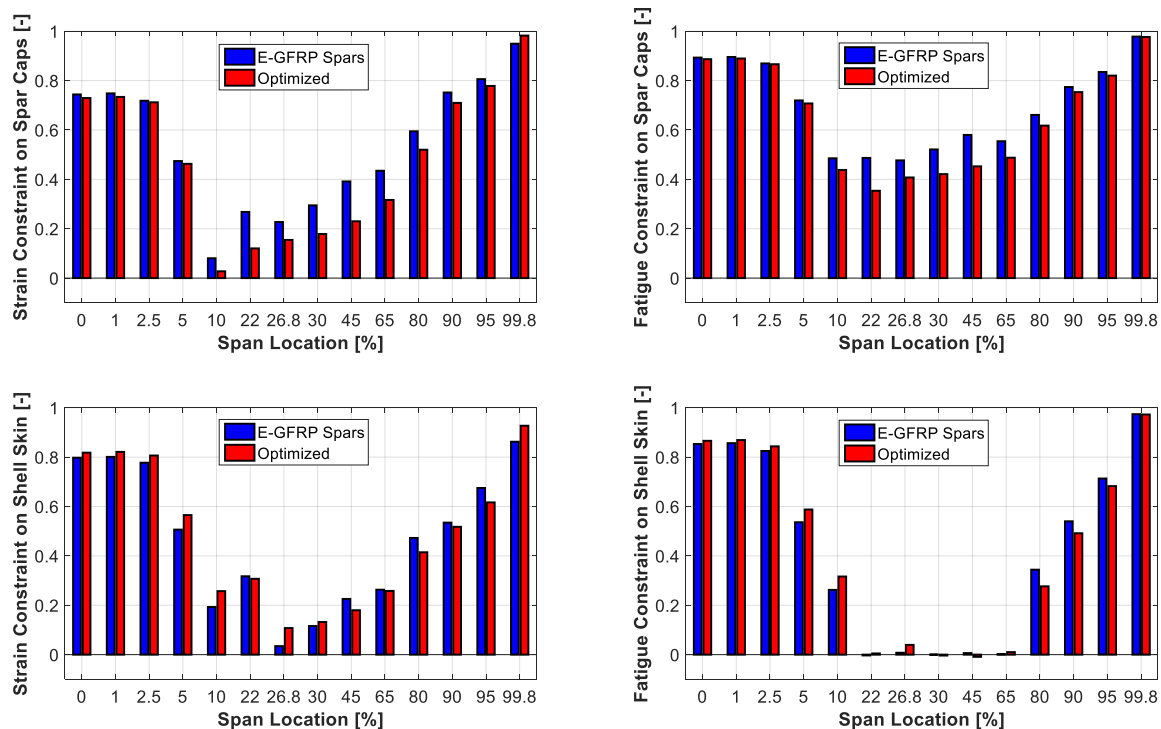


Figure 4: Comparison of strain (left) and fatigue (right) constraints on the spar caps (top) and on the shell skin (bottom) along blade span for the reference and the blade design with optimized spar caps laminate. Constraints are satisfied when positive.

structural studies. Overall, this means that each rotor design can be obtained in approximately 5 hours running on a workstation equipped with 56 logical processors.

In addition, sensitivity analyses are performed to challenge the robustness of the identified solution. First, assuming the materials of Class-A, results show the existence of a large plateau in an approximate range of ± 3 GPa around the optimum E_{11} identified by Cp-Max. In this range, a higher laminate index, which corresponds to higher laminate costs, causes smaller blade masses, but also increases blade costs by +1%. Vice versa, lower quality but cheaper laminates lead to heavier blades with similar blade costs. Moreover, the breakeven unit cost of H-GFRP, i.e. the unit laminate cost that gives no advantages compared to E-GFRP in terms of blade cost, is found to be 20% higher than the value assumed in Class-A. In the presence of a unit cost higher than this threshold, the optimum laminate index lies between E-GFRP and H-GFRP. Finally, the code is tested assuming a fourth imaginary laminate lying between H-GFRP and F-CFRP. Here, the solver converges to intermediate solutions depending on the assumed values for the unit cost.

3.4. Optimization of shell skin laminate

An approach equivalent to the one described in Sect. 3.2 and Sect. 3.3 is then followed for the optimization of the shell skin laminate. While a smaller room for improvements is identified by Cp-Max, results again show the functionality and the potential of the code. Indeed, as represented in the bar diagram in Fig. 5, the optimization solver identifies a potentially optimum laminate, which lies between Bx-GFRP and Tx-GFRP. This potentially optimum laminate is assumed with linearly interpolated mechanical properties and unit cost between the two existing laminates, and its use for the shell skin results in blade cost savings of 1.6%.

3.5. Simultaneous optimization of spar caps and shell skin laminates

The last study involved the simultaneous activation of the two composite indices. The solution found in this case is the one producing the largest advantages, namely -9.3% in blade mass and -2.9% in blade

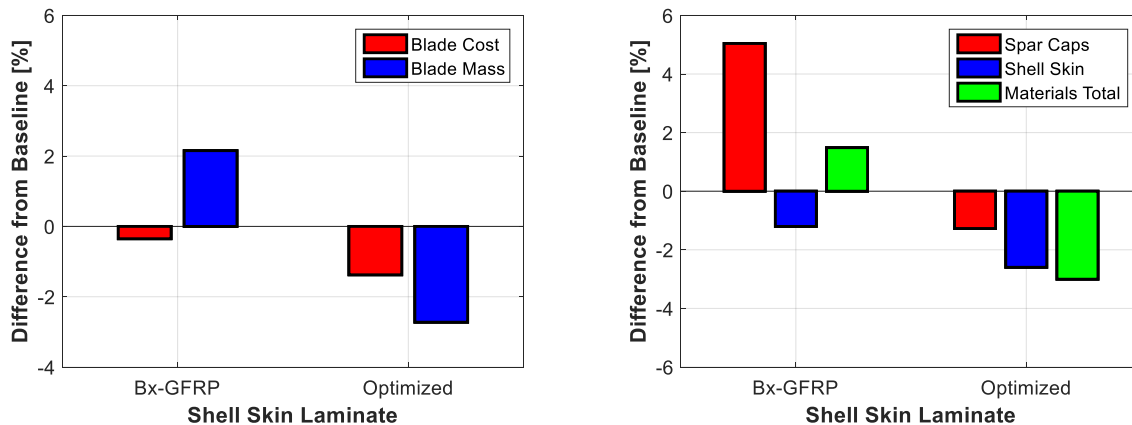


Figure 5: Blade cost and mass (left) and laminates cost (right) for the parametric and the automatic optimization study of the shell skin laminate.

cost with respect to the baseline design. The corresponding optima for the laminate indices are very close to the ones identified for the individual optimizations of Sect. 3.3 and Sect. 3.4, namely within a 0.8% difference.

4. Conclusions and outlook

The present work proposes a methodology to include the selection of the composite materials used in a wind turbine blade among the optimization variables of a holistic design process. The code is capable of capturing the structural trade-offs and identifying the best choice for the laminates in a complete automatic manner, leading to valuable improvements in the blade design process. A designer could then pick within a catalogue of existing materials the one that best matches the optimal solution computed by the proposed procedure. This method may also provide indications to composite manufacturers about potentially optimal combinations of mechanical properties and costs of the laminates, driving research and production.

The study is currently being extended to introduce new composite indices to guide the selection in the other structural components of the blade. Current plans also aim at investigating the potential benefits of adopting different laminates along the blade span within the same structural component, as well as estimating the potential advantages of the use of direct roving with fiber placement technologies, which would enable a better tailoring of the mechanical properties and a higher quality laminate at the price of higher manufacturing costs.

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